Florida Solar Energy Center
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Leakage Current Pathways, Magnitudes And Their Correlation TO Humidity And Temperature In High Voltage Biased Thin Film PV Modules

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Introduction

- Grid-connected PV systems must withstand high voltage bias in addition to harsh environmental conditions.
- High leakage currents (LC) can lead to electro-migration. Delamination and degradation are important issues for reliability and safety of thin-film PV modules.
- Delamination of SnO_2:F (TCO) is due to moisture ingress and electrochemical reaction at the TCO/EVA interface.

Introduction

- Sodium diffusion seems to have resulted in severe delamination of SnO_2:F layer from glass surface.
- Heat, humidity and voltage, either separately or in combination are probably active in delamination mechanism.
- Correlation of leakage current with RH, temperature and time under high voltage bias in hot and humid conditions due to moisture percolation and saturation within the PV module studied in this paper.

High Voltage Bias Test Bed

- Florida Solar Energy Center (FSEC) high voltage test bed consists of eight superstrate type BP Solar a-Si:H modules installed at following bias conditions.

  +600 V and –600 V each

  +300 V and –300 V each

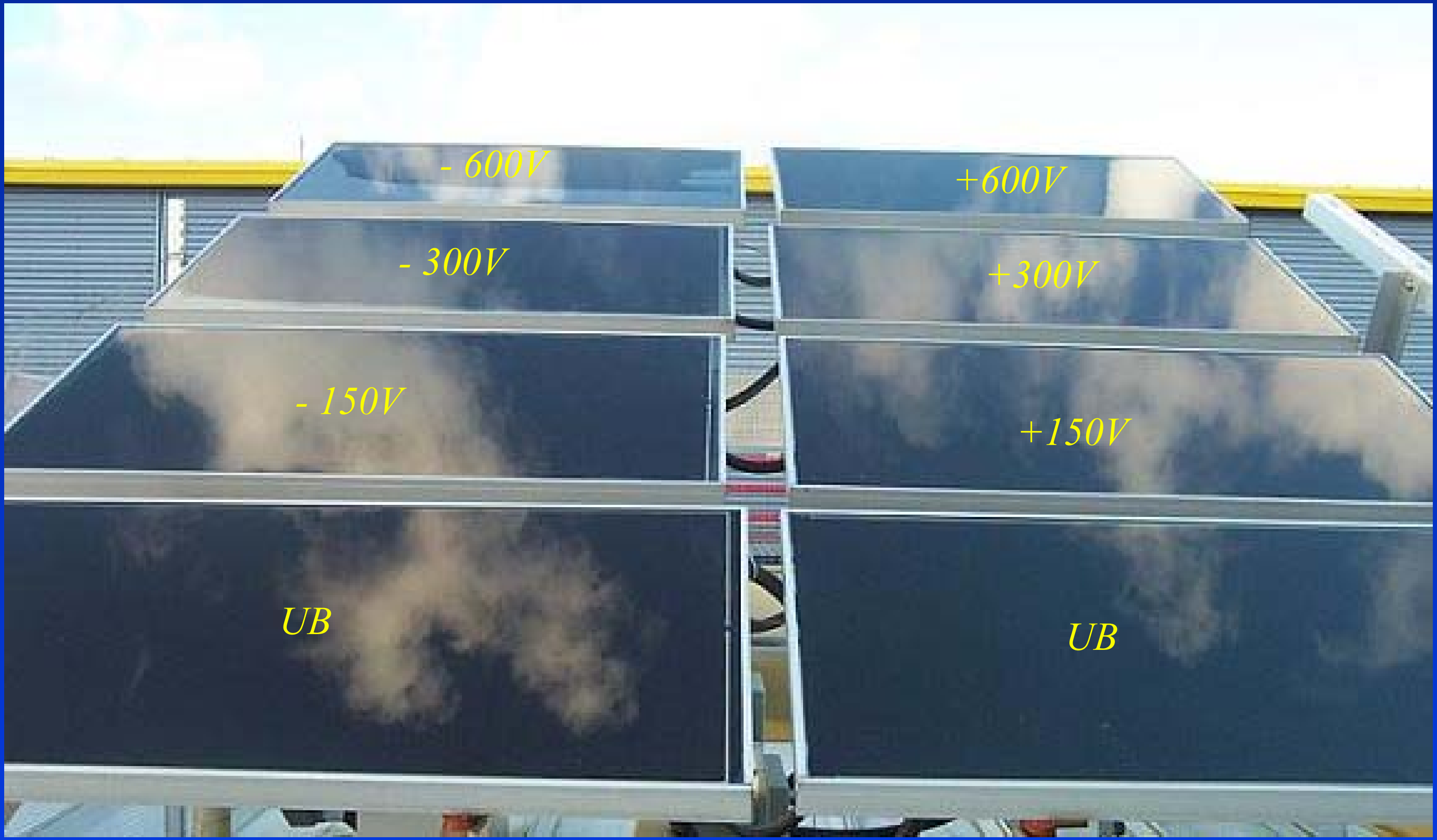
  +150 V and –150 V each

  No bias – 2 Nos.
- FSEC high voltage test bed also has 2 modules each from First Solar, Shell Solar and Uni-Solar each biased at +600V and –600V individually.

High Voltage Bias Test Bed

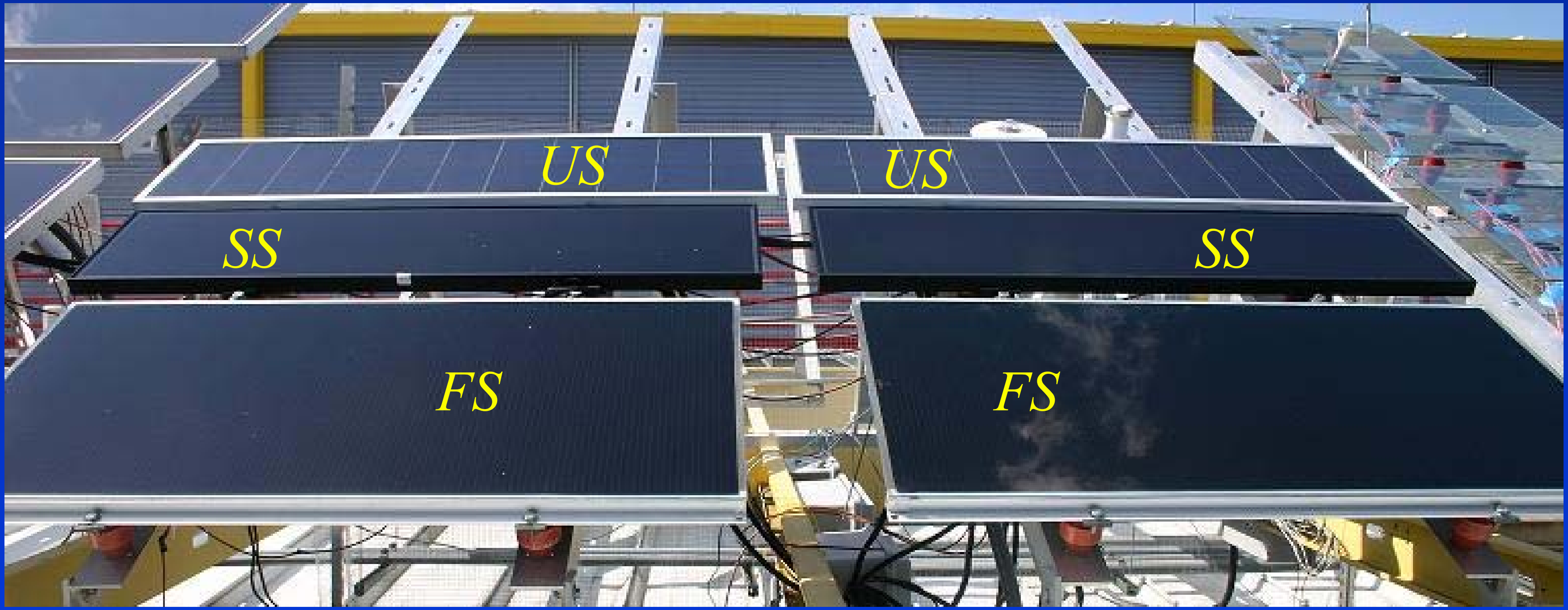
- PV modules are monitored for leakage currents, back of the module temperature, ambient temperature, solar irradiance and relative humidity.
- Readings are taken at an interval of 15 seconds and average of all these readings for every 2 minutes are recorded.

BP Solar HV Test Bed



24 Months of exposure

NREL HV Test Bed



8 Months of Exposure

NREL Outdoor Monitoring Test Bed

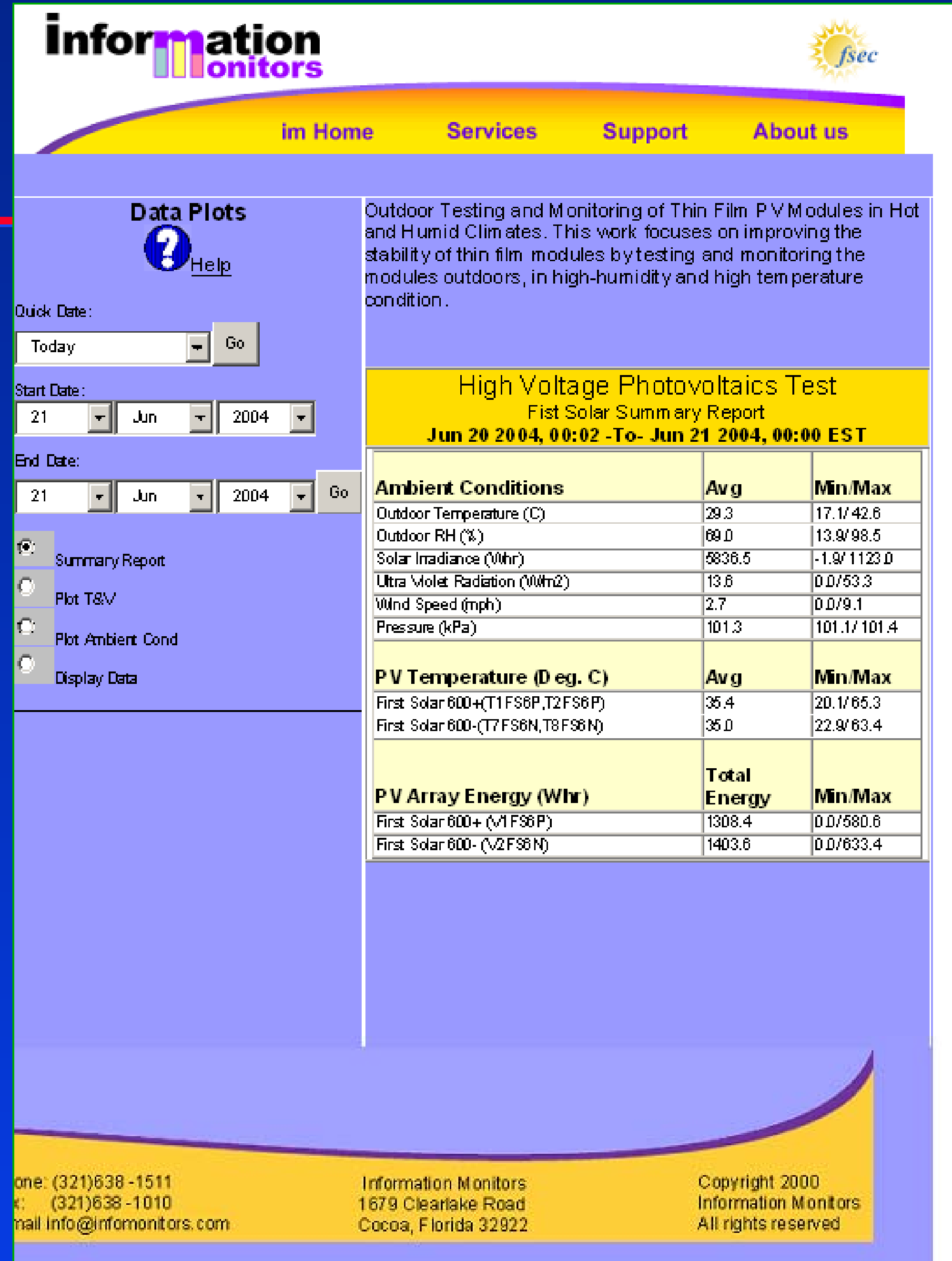
- NREL outdoor monitoring high voltage test bed consists of First Solar (FS) (6+6), Shell Solar (SS) (24+24) and Uni-Solar (US) (20+20) Modules.
- Installation:

FS – Sep 2003

SS – Oct 2003

US – Nov 2004

FS Array Home Page



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Start Date: 21 Jun 2004

End Date: 21 Jun 2004 Go

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Plot Ambient Cond

Display Data

Outdoor Testing and Monitoring of Thin Film PV Modules in Hot and Humid Climates. This work focuses on improving the stability of thin film modules by testing and monitoring the modules outdoors, in high-humidity and high temperature condition.

High Voltage Photovoltaics Test

Fist Solar Summary Report

Jun 20 2004, 00:02 -To- Jun 21 2004, 00:00 EST

Ambient Conditions	**Avg**	**Min/Max**
Outdoor Temperature (C)	29.3	17.1/ 42.6
Outdoor RH (%)	69.0	13.9/ 98.5
Solar Irradiance (Whr)	5836.5	-1.9/ 1123.0
Ultra Violet Radiation (W/m2)	13.6	0.0/ 53.3
Wind Speed (mph)	2.7	0.0/ 9.1
Pressure (kPa)	101.3	101.1/ 101.4

PV Temperature (Deg. C)	**Avg**	**Min/Max**
First Solar 600+(T1FS6P,T2FS6P)	35.4	20.1/ 65.3
First Solar 600-(T7FS6N,T8FS6N)	35.0	22.9/ 63.4

PV Array Energy (Whr)	**Total Energy**	**Min/Max**
First Solar 600+ (V1FS6P)	1308.4	0.0/ 580.6
First Solar 600- (V2FS6N)	1403.6	0.0/ 633.4

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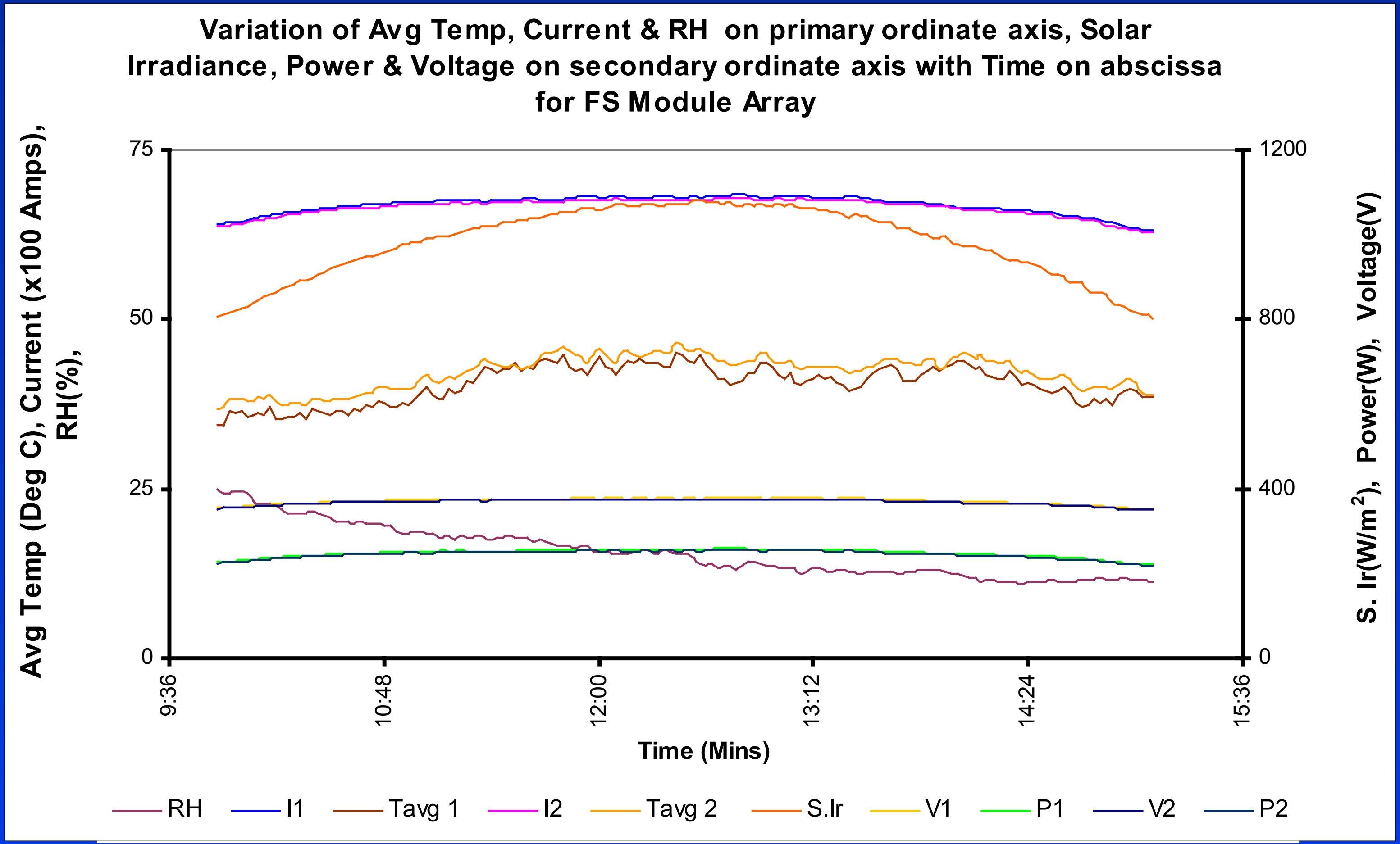
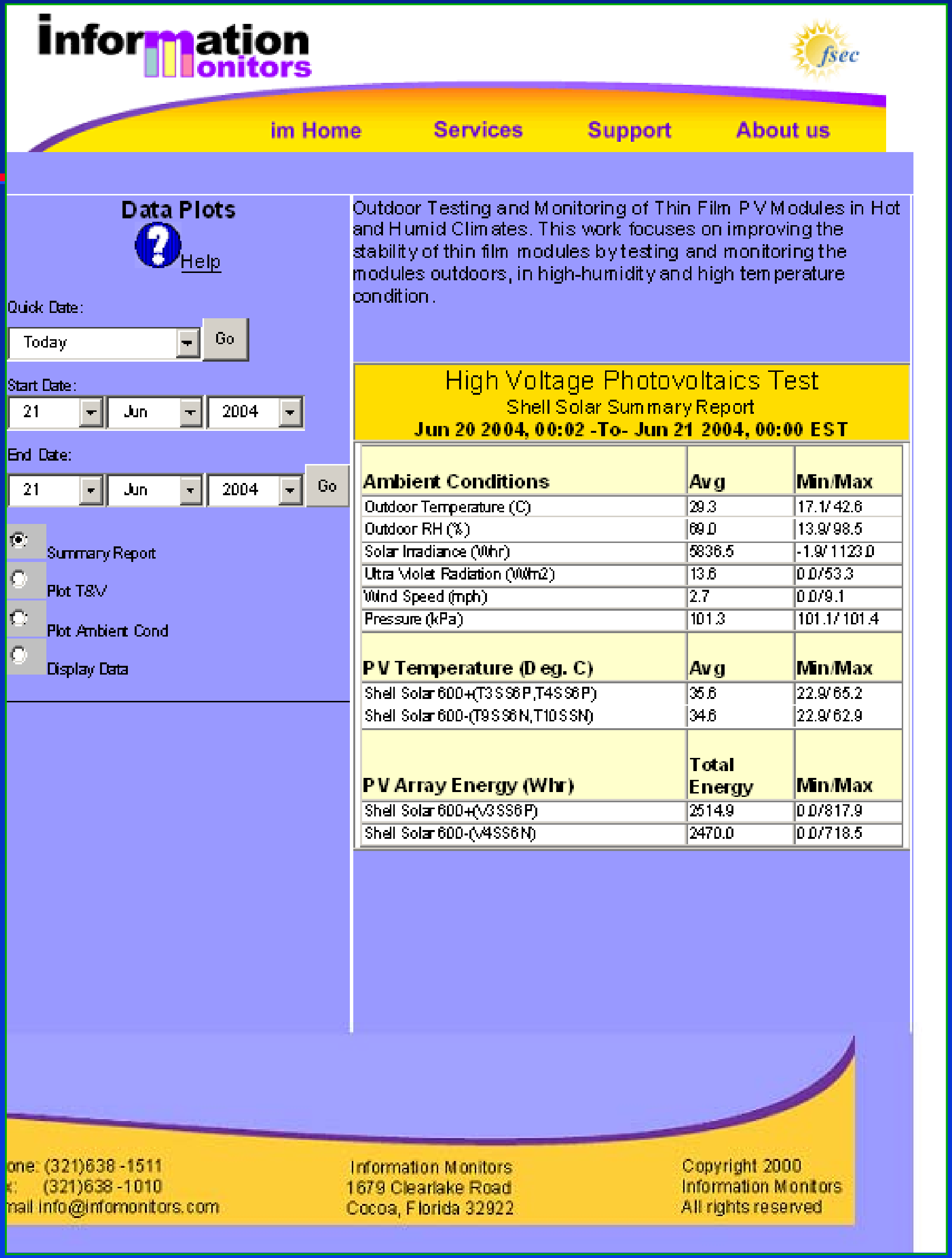
FS +600V Array

FS -600V Array

FS Solar Array Variation



SS Array Home Page



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- Plot T&V
- Plot Ambient Cond
- Display Data

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High Voltage Photovoltaics Test

Shell Solar Summary Report

Jun 20 2004, 00:02 -To- Jun 21 2004, 00:00 EST

Ambient Conditions	**Avg**	**Min/Max**
Outdoor Temperature (C)	29.3	17.1/42.6
Outdoor RH (%)	69.0	13.9/98.5
Solar Irradiance (Whr)	5836.5	-1.9/1123.0
Ultra Violet Radiation (W/m2)	13.6	0.0/53.3
Wind Speed (mph)	2.7	0.0/9.1
Pressure (kPa)	101.3	101.1/101.4
PV Temperature (Deg. C)	**Avg**	**Min/Max**
Shell Solar 600+(T3SS6P,T4SS6P)	35.6	22.9/65.2
Shell Solar 600-(T9SS6N,T10SSN)	34.6	22.9/62.9
PV Array Energy (Whr)	**Total Energy**	**Min/Max**
Shell Solar 600+(V3SS6P)	2514.9	0.0/817.9
Shell Solar 600-(V4SS6N)	2470.0	0.0/718.5

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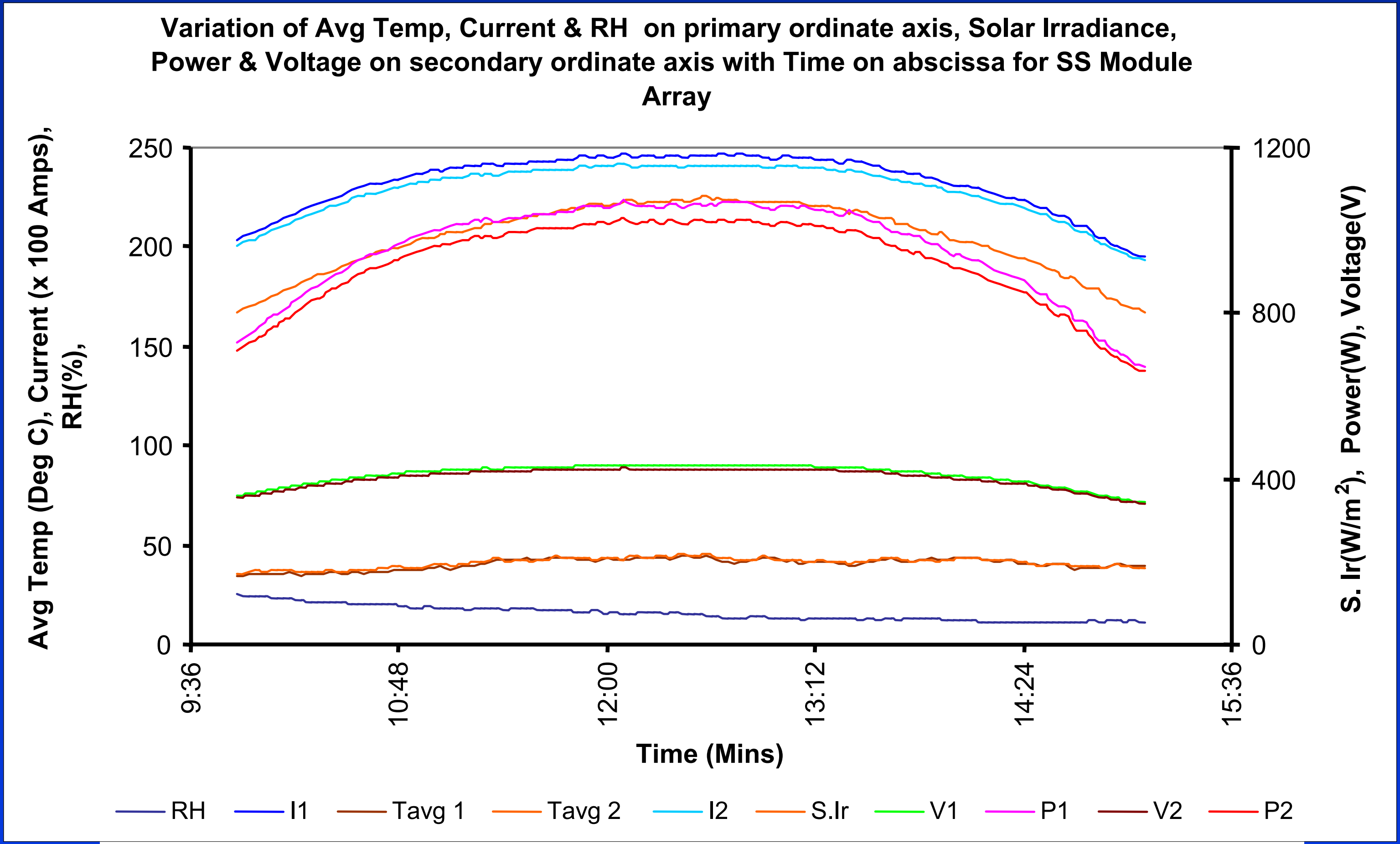
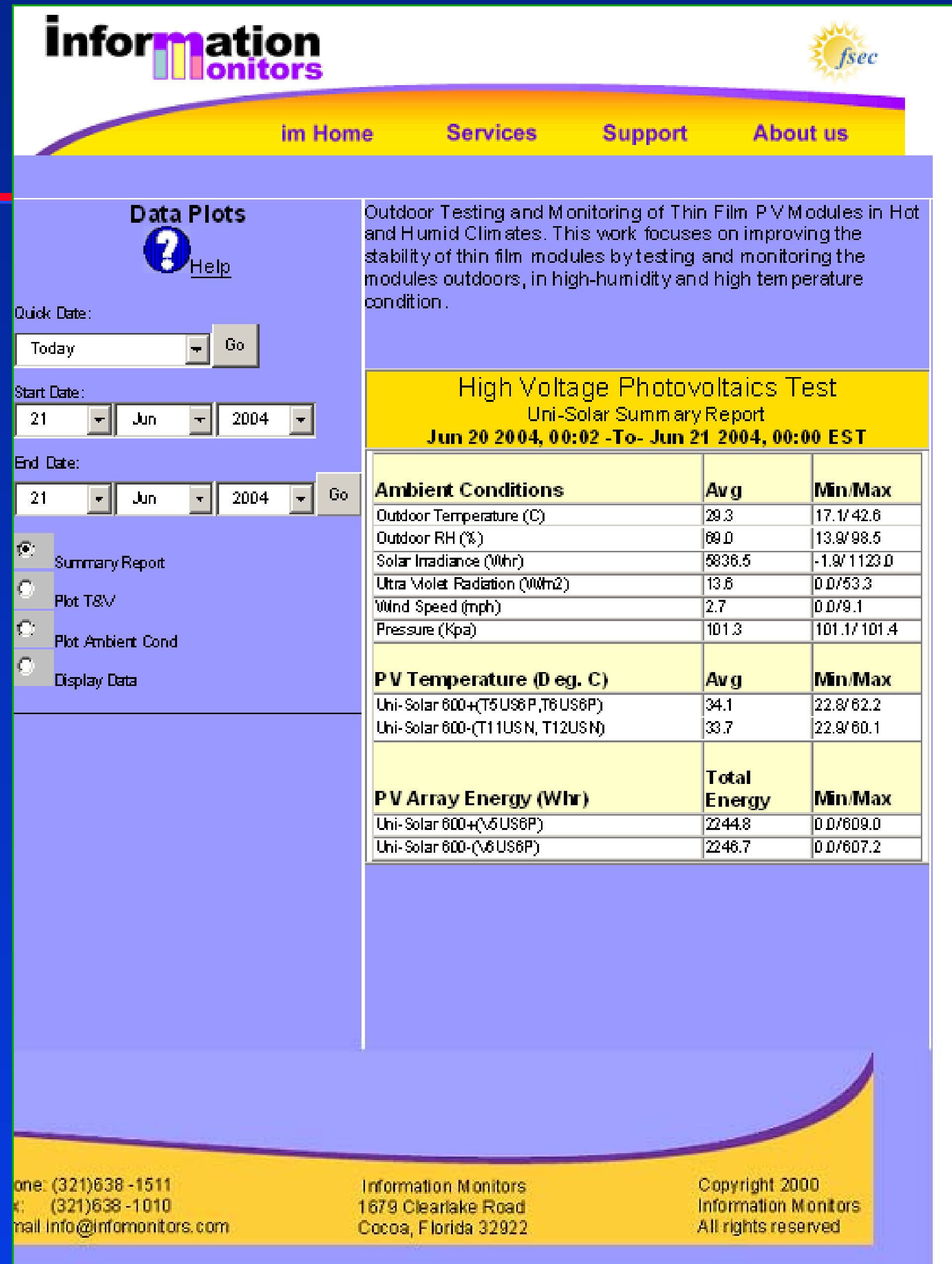
SS +600V Array

SS -600V Array

SS Solar Array Variation



US Array Home Page



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Start Date: 21 Jun 2004

End Date: 21 Jun 2004 Go

Summary Report

Plot T&V

Plot Ambient Cond

Display Data

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High Voltage Photovoltaics Test

Uni-Solar Summary Report

Jun 20 2004, 00:02 -To- Jun 21 2004, 00:00 EST

Ambient Conditions	**Avg**	**Min/Max**
Outdoor Temperature (C)	29.3	17.1/ 42.6
Outdoor RH (%)	69.0	13.9/ 98.5
Solar Irradiance (Whr)	5836.5	-1.9/ 1123.0
Ultra Violet Radiation (W/m2)	13.6	0.0/ 53.3
Wind Speed (mph)	2.7	0.0/ 9.1
Pressure (Kpa)	101.3	101.1/ 101.4

PV Temperature (Deg. C)	**Avg**	**Min/Max**
Uni-Solar 600+(T5US6P,T6US6P)	34.1	22.8/ 62.2
Uni-Solar 600-(T11USN, T12USN)	33.7	22.9/ 60.1

PV Array Energy (Whr)	**Total Energy**	**Min/Max**
Uni-Solar 600+(V5US6P)	2244.8	0.0/609.0
Uni-Solar 600-(V6US6P)	2246.7	0.0/607.2

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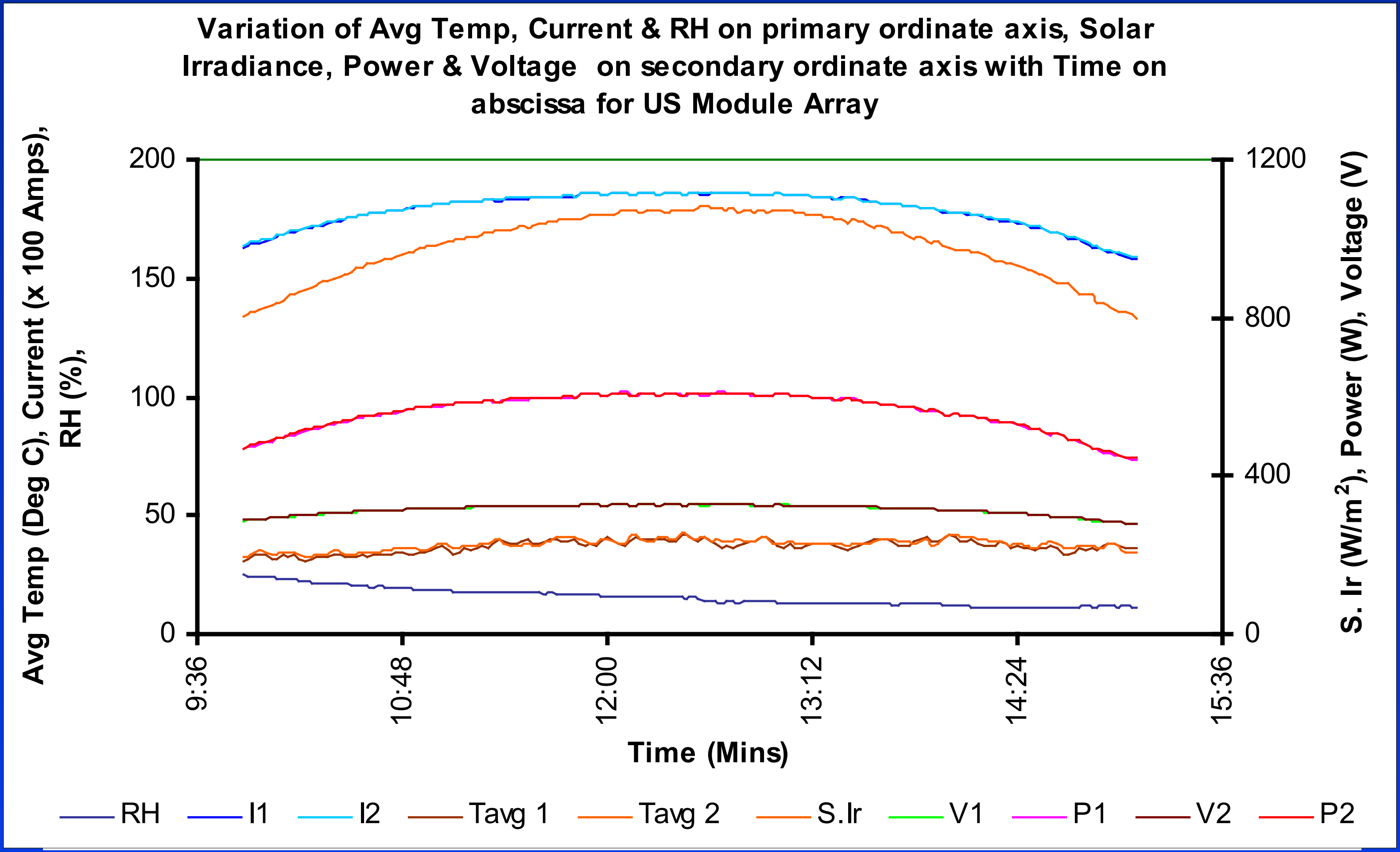
US +600V Array

US –600V Array

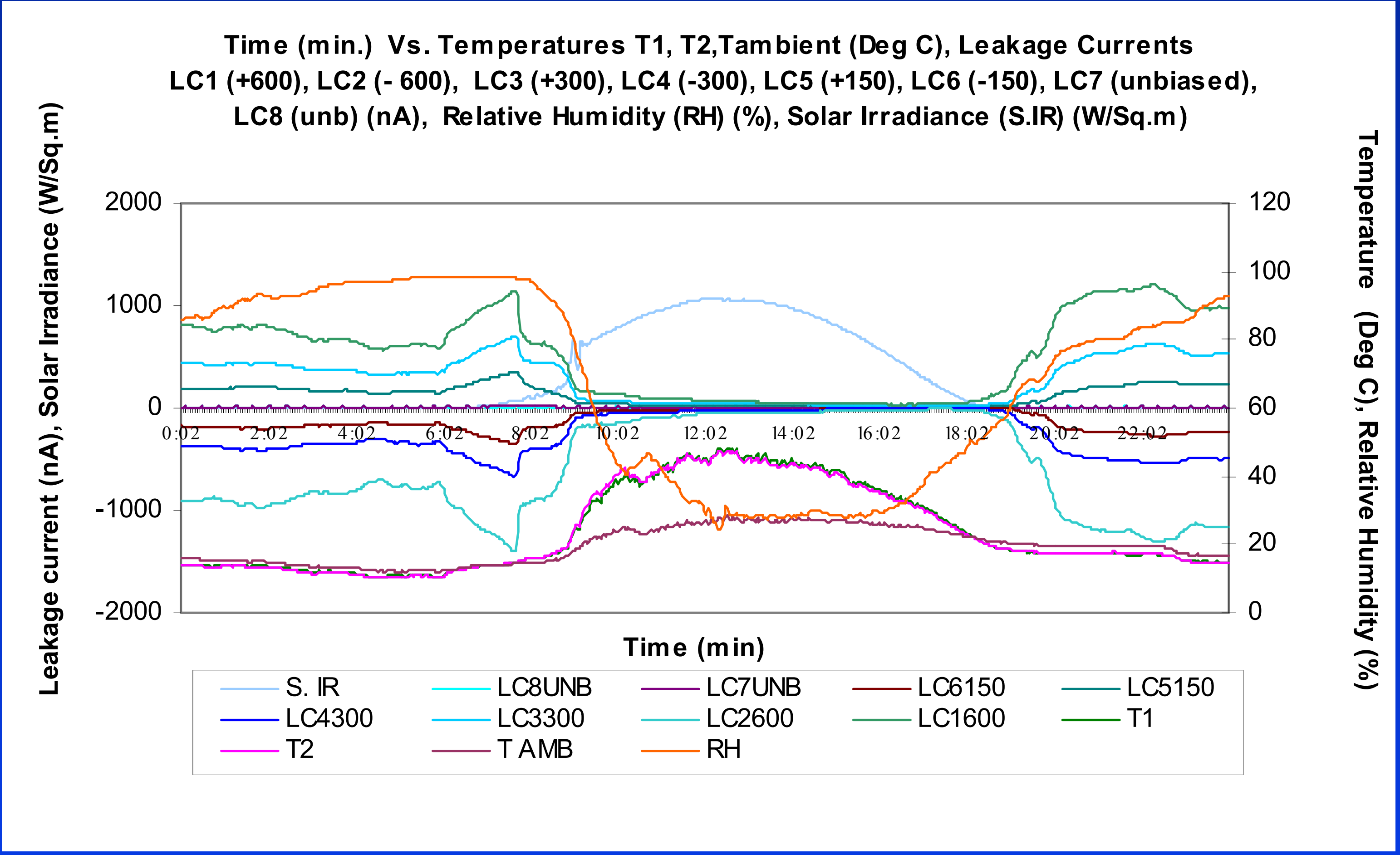
US Solar Array Variation



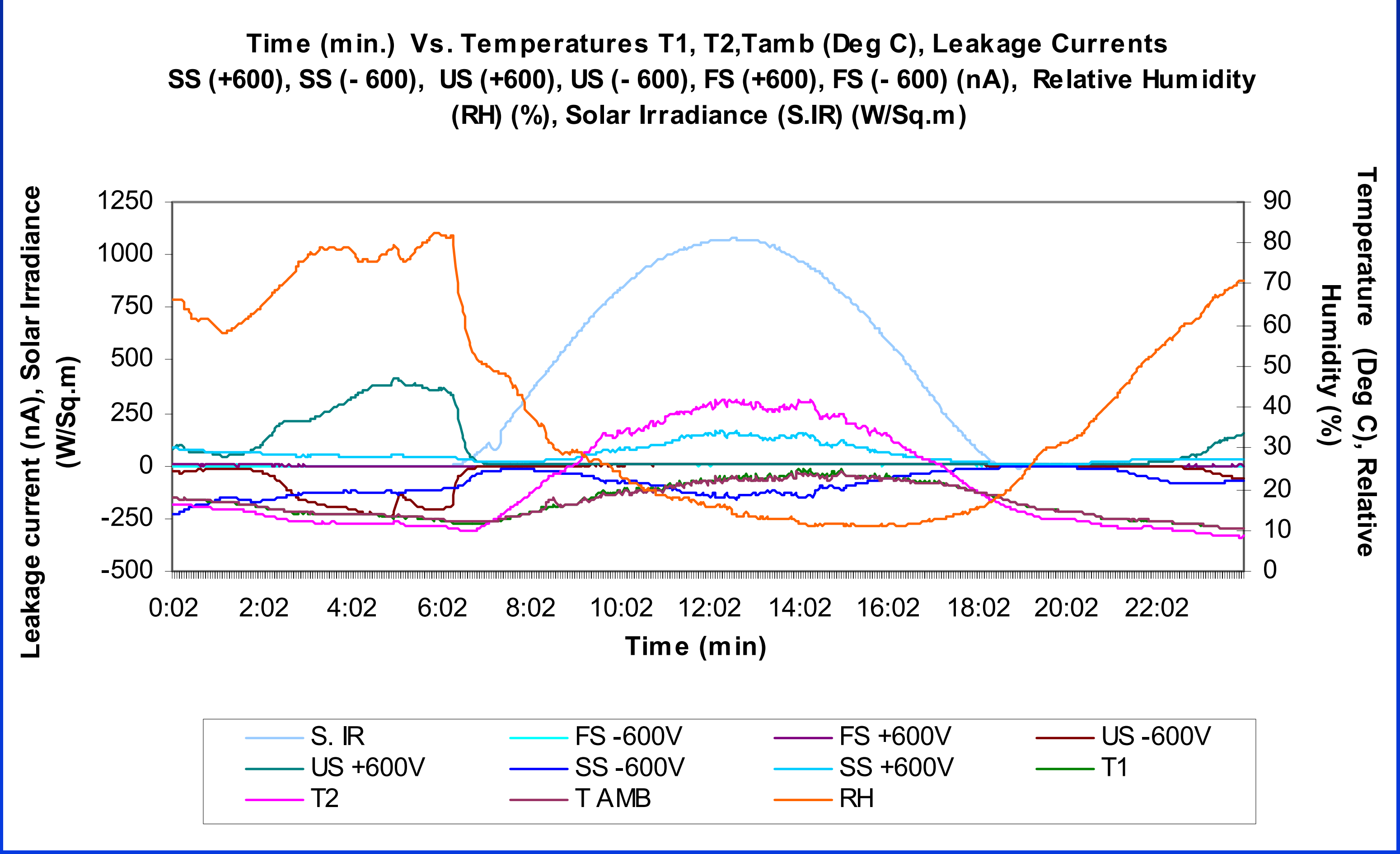
Results and Discussions

- Researchers at the JPL and NREL have developed module acceleration test in a controlled atmosphere.
- Both the JPL and NREL work have indicated humid environment, elevated temperature, and a voltage bias between the module frame and the thin film device as cause of thin film module corrosion.
- Study of correlation of LC with RH and temperature is essential.

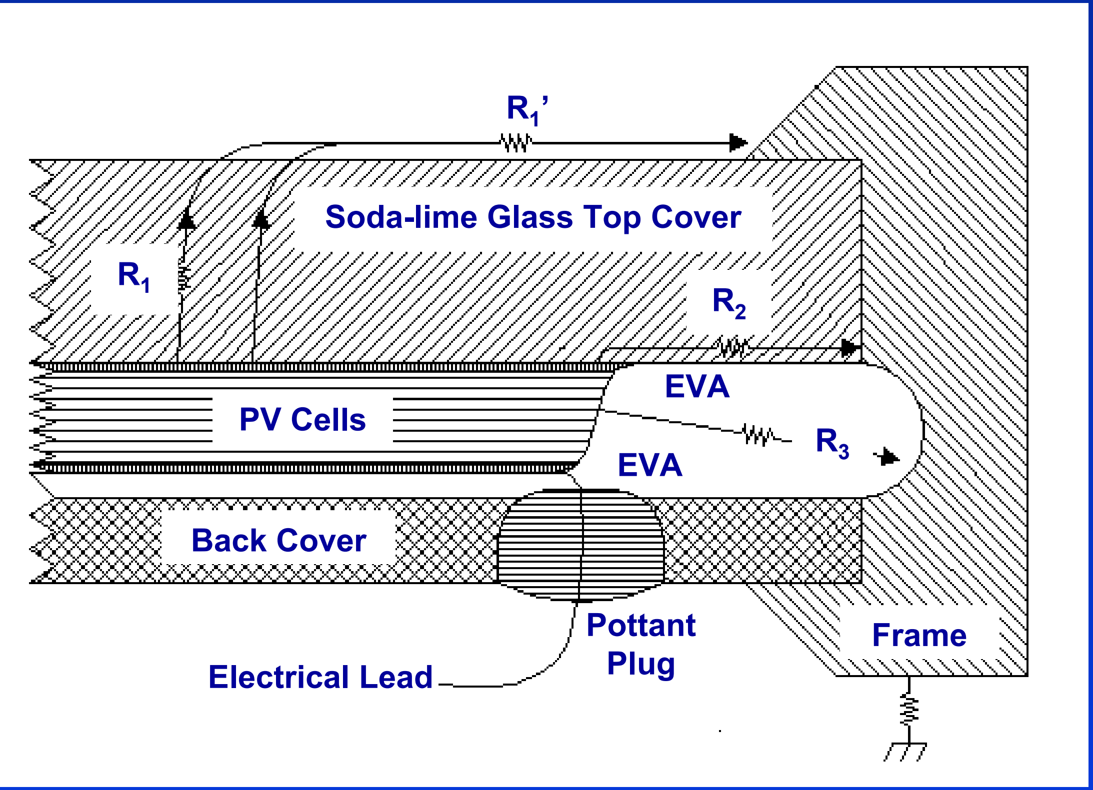
LC Variation-BP Solar Array



LC Variation – NREL



Cross Section Of The Module



- R_1' - Surface resistance of the SLG,
- R_1 - SLG bulk resistance.
- R_2 – Encapsulant-SLG interface resistance.
- R_3 - Encapsulant bulk resistance

Leakage Currents Paths

- The dominant LC path during the night i.e., moderately low temperature and high humidity are surface (R_1') and through the SLG (R_1).
- EVA/glass interface (R_2) and EVA (R_3) account for the LC paths during the day time.
- As the RH and temperature increases the LC decrease.

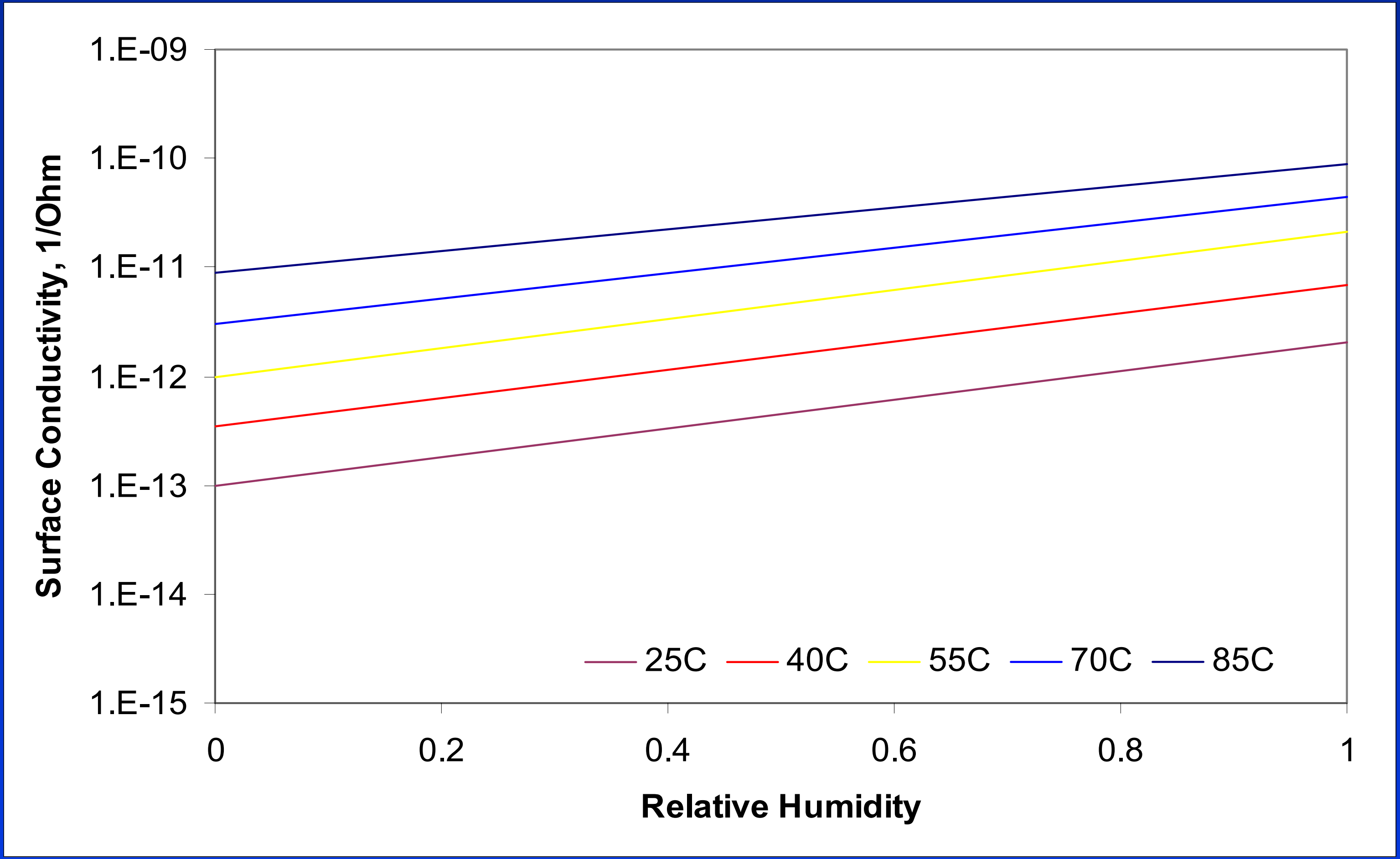
Leakage Current Calculation

- Excess current due to poor module design, flaws during fabrication, or in the junction box are not considered.
- Resistance of the edge gasket volume between the metal frame and the module edge is assumed to be zero when compared to SL glass bulk or surface.
- Leakage through the back cover material and EVA covering the back of the cells is not considered.

Calculation Parameters

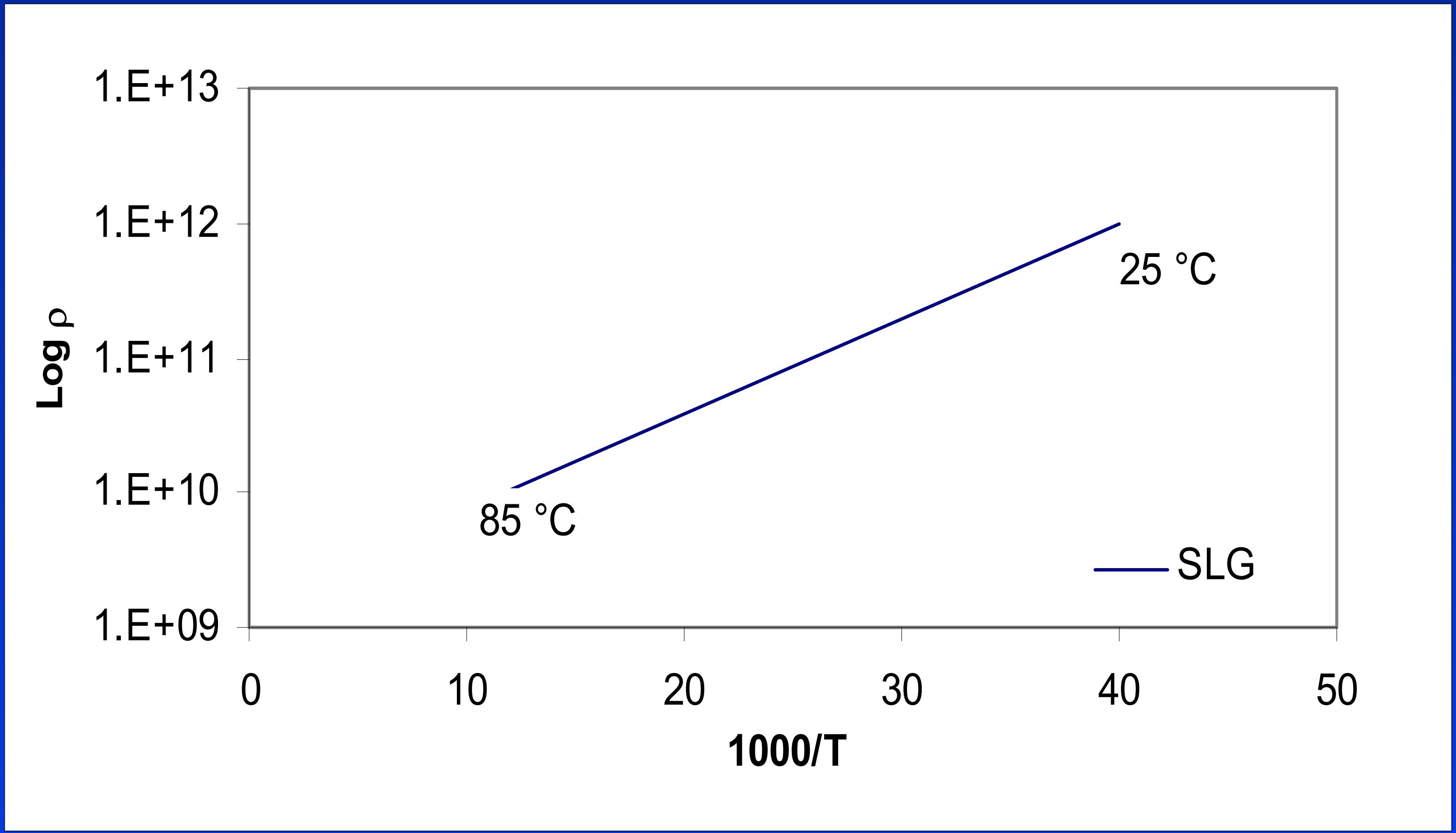
- Length and breadth of the module - ~121 & ~60 cms respectively.
- Perimeter of the module is ~358 cms.
- Thickness of SLG ~ 0.3 cm.
- Edge delete – 1cm.

Surface Conductivity of SLG



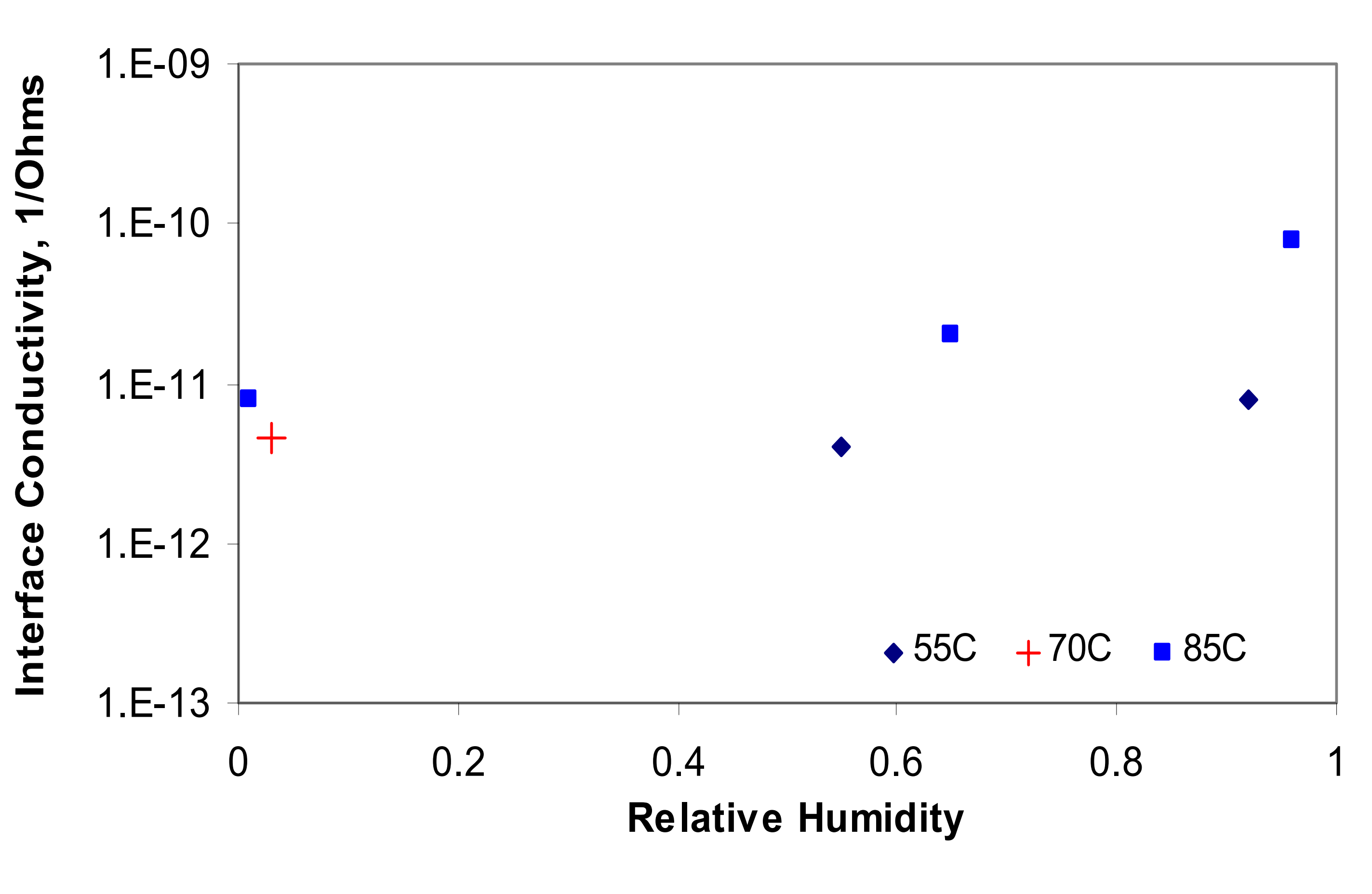
Ref : G. Mon, et.al

Bulk Conductivity of SLG



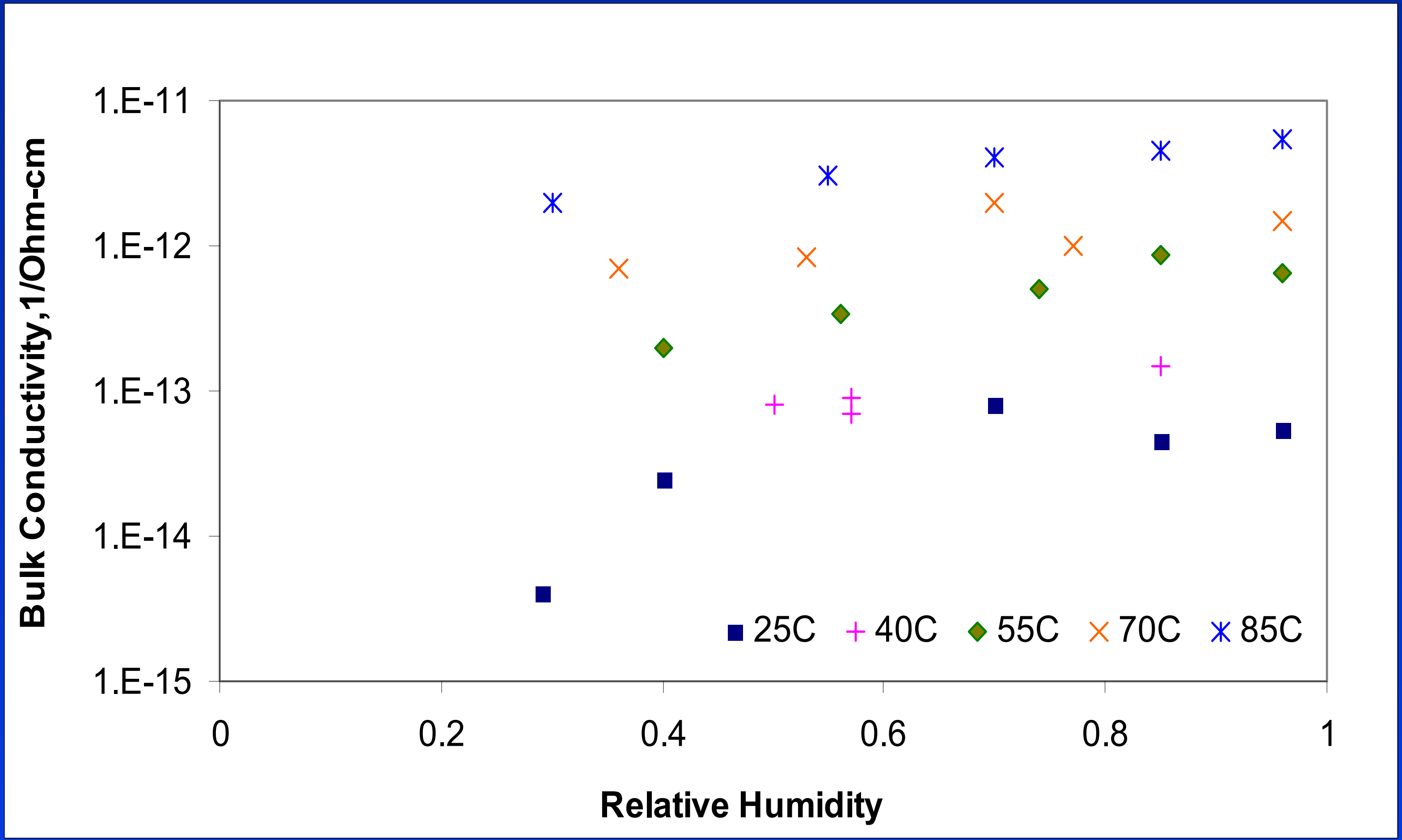
Ref : H. E. Hagy

Interface Conductivity, EVA/SLG



Ref : G. Mon, et.al

Bulk Conductivity of EVA



Ref : G. Mon, et.al

Contribution of Each Resistance in Giga Ohms, Measured and the Calculated LC

Climate, Noon/Night	T_{Avg}	RH	R_1	R_1'	R_2	R_3	R_{eff}	Leakage Currents (nA)	
	(°C)	%	$10^9\ \Omega$					Cal.	Measured
Clear, Noon	39.1	12.8	0.00323	5.59	6.99	93.17	3.01	199	92
Clear, Noon	40.7	8.2	0.00323	5.59	7.99	93.17	3.18	189	28
Clear, Night	21.1	81.1	0.12109	3.49	6.99	93.17	2.32	258	1454
Clear, Night	12.7	86.6	28.25526	6.99	14.00	139.76	9.34	64	1072
Cloudy, Noon	37.4	46.3	0.00283	2.80	3.99	46.59	1.59	378	49
Cloudy, Noon	38.7	45.9	0.00363	2.80	14.00	39.93	2.20	272	228
Cloudy, Night	19.6	87.4	0.20182	3.49	6.99	93.17	2.36	255	1742
Cloudy, Night	19.0	77.8	0.20182	3.99	9.32	139.76	2.83	212	459

Experimental Results

- The most destructive condition at the SnO_2/glass interface exists for a cell biased negatively relative to ground.
- Na ions capable of reducing adhesion at the EVA/glass interface.
- The SnO_2 layer and the cells deposited on glass crack and curl into the EVA.
- Result – Bar Graph damage patterning.

-600V Biased Module

24 Months of exposure

-600V Biased Module

14 Months of exposure

-300V Biased Module

30 Months of exposure

-150V Biased Module

30 Months of exposure

Unbiased Module

30 Months of exposure

Leakage Currents

- The measured values at noon are lower than the calculated values whereas the measured values are much higher than the calculated values at night on both clear days and cloudy days.
- The measured values are much higher at night because during night time the module is soaked in humid ambient for extended period of time.

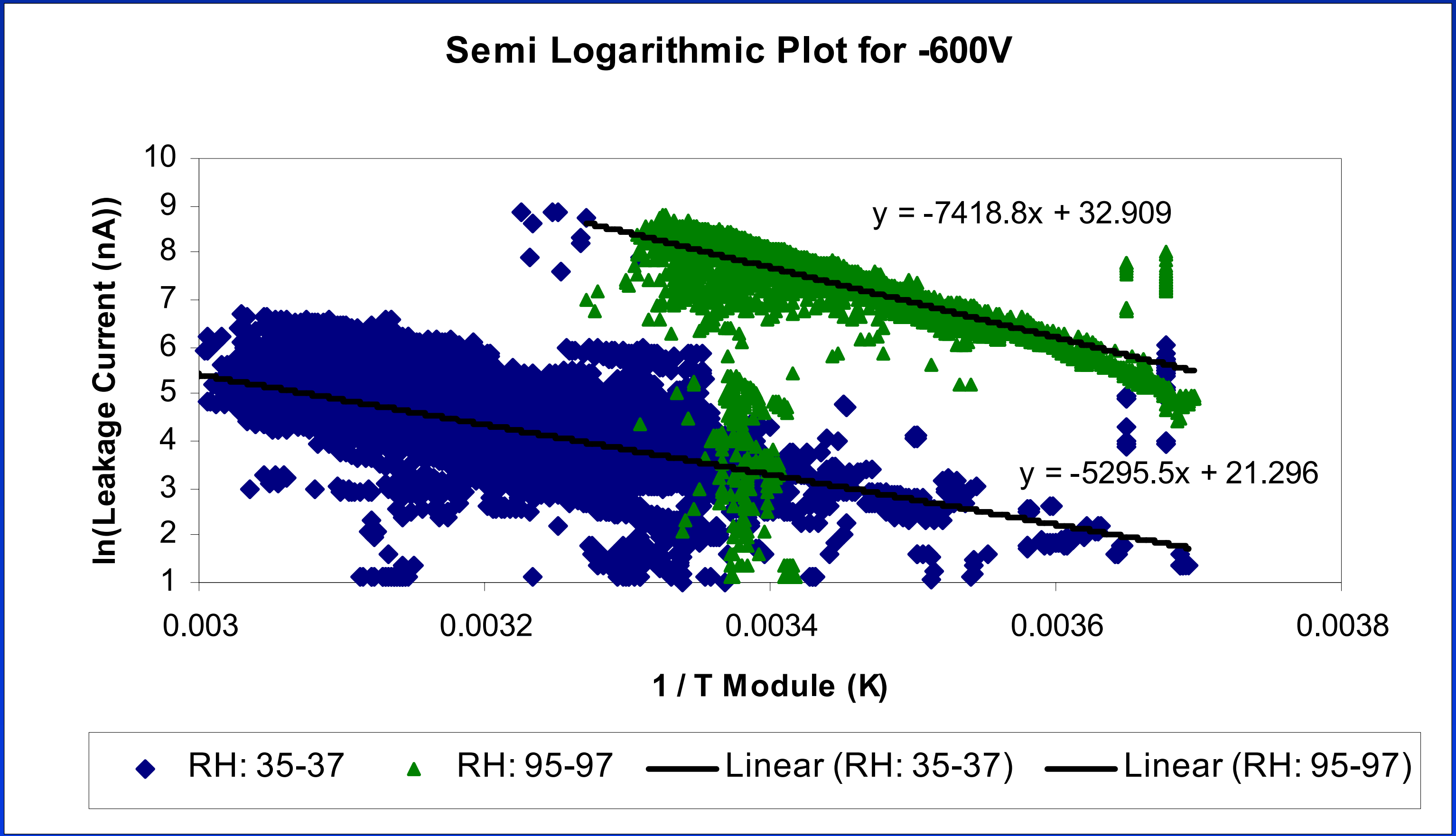
Activation Energy

- Leakage currents increase exponentially with the reciprocal of the module temperature.
- The activation energies calculated as

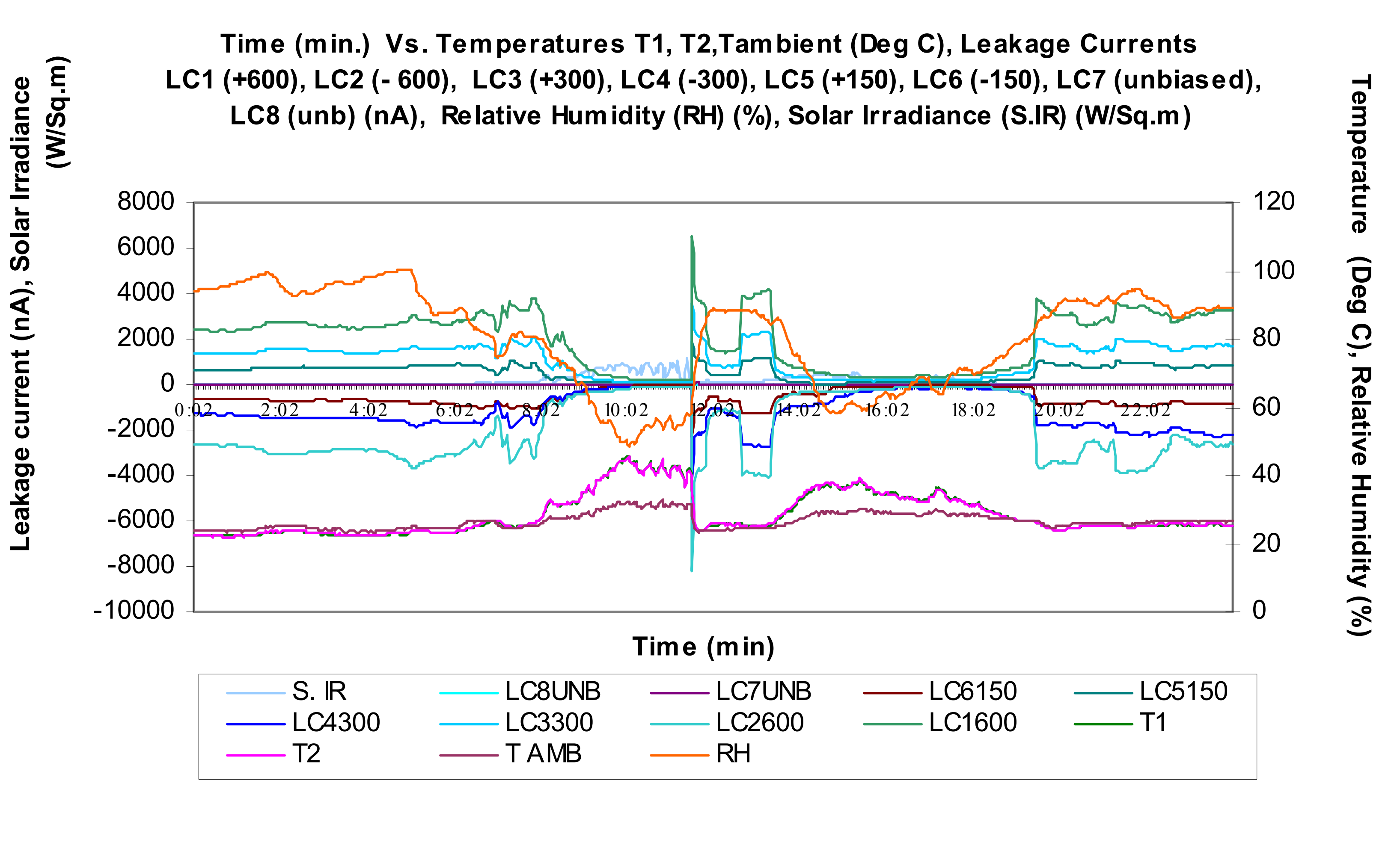
  $i\ (RH, Vb, T) = i_0\ (RH, Vb)\ \exp\ (- EA\ (RH)/kT)$

  where EA (RH) - activation energy as a function of RH, k - Boltzmann's Constant, T – Absolute Module Temperature in Kelvin were 0.456 eV and 0.639 eV for RH of 35-37% and 95-97% resp.
- Characteristic activation energy depends on RH. At high RH, the activation energies are larger than those at low RH for all the high-voltage biased modules.

Arrhenius Semi-log Graph



Leakage Currents – Cloudy Day



Leakage Currents

- Charge accumulates on the glass surface when the temperatures are high and RH is low due to high conductance of the bulk glass and low conductance of the glass surface.
- Sudden rise in RH due to sudden drop in temperature result in sharp LC rise.
- Moisture accumulation and saturation results in transients of high LC.

Conclusion

- The leakage currents generated in biased PV module are functions of both relative humidity and temperature.
- Surface and bulk glass conductivities dominate in the leakage current generation under wet conditions.
- The surface, bulk glass, EVA/glass interface and bulk EVA conductivities govern under dry conditions.

Conclusion

- The measured values at noon are lower than the calculated values and those measured at night are much higher on both clear as well as cloudy day.
- PV module leakage conductance is thermally stimulated with a characteristic activation energy that depends on RH.
- The activation energy were 0.456 eV and 0.639 eV for RH of 35-37% and 95-97% respectively.

Acknowledgements

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- The authors are thankful to John Wohlgemuth, BP Solar, Joe del Cueto and Carl Osterwald, NREL and Michael A. Quintana and David L. King SNL for assistance in setting up the high voltage test bed and for useful discussions.